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NOAA Technical Report NESDIS 69

NONLINEARITY CORRECTIONS FOR THE THERMAL INFRARED CHANNELS OF THE ADVANCED VERY HIGH RESOLUTION RADIOMETER: ASSESSMENT AND RECOMMENDATIONS

Washington, D.C.
June 1993

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

National Oceanic and Atmospheric Administration
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National Environmental Satellite, Data, and Information Service
Gregory W. Withee, Acting Assistant Administrator

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Prefatory Note

This report on the nonlinearity corrections to be implemented to facilitate proper interpretation of the measurements made in the thermal infrared channels (Channel 4: ≈ 10.3-11.3μm; Channel 5: ≈ 11.5-12.5μm) of the Advanced Very High Resolution Radiometer onboard the NOAA-7 and -9 spacecraft is based on the work done by Charles Walton and Jerry Sullivan at the NOAA/NESDIS Satellite Research Laboratory, Camp Springs, Maryland; and by Jim Brown and Robert Evans at the University of Miami, Miami, Florida. I have drawn freely from their verbal and written contributions in the preparation of this report. The report has been reviewed by the members of the AVHRR Pathfinder Calibration Working Group and other contributors and interested scientists. However, I have taken the final decision regarding the format and contents of the report in my capacity as the Chair of the AVHRR Pathfinder Calibration Working Group.

C. R. Nagaraja Rao

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ABSTRACT

The NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Calibration Working Group has for one of its main objectives the development of procedures to correct measurements made in the thermal infrared channels (channel 4: $\approx$10.3-11.3μm; channel 5: $\approx$11.5-12.5μm) of the AVHRR for the nonlinear response of the Mercury-Cadmium-Telluride (Hg-Cd-Te) detectors used in the two channels. Toward this end, two correction procedures, one based on the measured linear brightness temperatures in the two channels, and the other on the linear radiances in the two channels, were examined and compared in detail. Pre-launch thermal-vacuum test data were used in this comparison. The results of the comparison indicated that the radiance-based correction procedure performed better than the temperature-based procedure over the entire range of scene temperatures ($\approx$200-325°K) normally encountered, while the two procedures were equally effective at the higher scene temperatures. Based on these findings, it is recommended that the radiance-based procedure be used in the reprocessing of the AVHRR Pathfinder data. Procedural details, formulae, and required data are given for channels 4 and 5 of the AVHRRs on NOAA-7 and -9 spacecraft.

1. Introduction

The NOAA/NASA Pathfinder program has for its primary objective the establishment of accurate, long-term records of environmental parameters that can be used in climate and global change studies. This task entails the generation of atmospheric and surface products such as global cloud climatology, land cover, global aerosol burden, sea surface temperature, etc., that can be used both as diagnostic and prognostic tools in the simulation and assessment of the impact of anthropogenic and natural phenomena on the environment. It is also expected, according to the Memorandum of Understanding executed between NOAA and NASA (1989, 1990), that this program will provide a learning experience in the application of long-term time series and large volume data sets to climate and global change research, and will lead to the definition of community-consensus derived products and to the development of plans to generate and, with user participation, to quality control and validate the same products. As the name implies, it is hoped that the Pathfinder program would prepare the scientific community to explore the uncharted areas of acquisition, storage, analysis, and interpretation of the very large amounts of geophysical data that will result from the multinational, multidisciplinary missions to study Planet Earth, such as the Earth Observing System (EOS), and the Advanced Earth Observing System (ADEOS) planned for coming decades.

It is apparent in this context that the continuous, long-term records of atmospheric and surface data obtained with the meteorological satellites such as the NOAA Polar-orbiting, operational, environmental satellite (POES), the Geostationary Operational Environmental Satellite (GOES), and with the spacecraft flown under the Defense Meteorological Satellite Program (DMSP) should form the core of this climate and global change data base. Thus, separate Pathfinder programs have been established for the Advanced Very High Resolution Radiometer (AVHRR), the Tiros Operational Vertical Sounder (TOVS) suite of measurements, GOES, and the Special Sensor Microwave/Imager (SSMI) of the DMSP (e.g., Ohring and Dodge, 1992). Initially, the retrospective calibration, reprocessing, and interpretation of operational products generated using these data would be confined to the Pathfinder period, 1981-1991.

The utility of the long-term environmental data records assembled under the Pathfinder programs would essentially be determined by the accuracy and quality (internal consistency and completeness) of the satellite-derived information. Thus, to ensure the quality of the reprocessed AVHRR data for the Pathfinder period, the AVHRR Pathfinder Calibration Working Group was constituted in March 1991; its membership is made up of representatives of the AVHRR Pathfinder Atmosphere, Land, and Ocean Working Groups, and other calibration scientists (see Appendix B for a list of members). The Working Group was charged with the tasks of (a) assessment of the in-orbit degradation of the visible and near infrared channels (Channel 1: $\approx$0.58-0.68μm; Channel 2: $\approx$0.72-1.05μm) of the AVHRRs onboard NOAA-7, -9, and -11 spacecraft since there are no onboard calibration devices for these channels, and (b) development of a consistent set of in-flight calibration algorithms for the AVHRR thermal infrared channels (Channel 4: $\approx$10.3-11.3μm; Channel

5: $\approx$11.5-12.5μm). It was further understood that under task (b), the development of appropriate correction procedures for the nonlinear response of the detectors in channels 4 and 5 would be addressed first.

It was decided at the AVHRR Pathfinder Calibration Working Group meeting held on October 5-6, 1992 (NOAA Science Center, Camp Springs, Maryland), that two preliminary reports should be written, one addressing the degradation of the visible and near infrared channels, and the other the non-linearity corrections to the measurements made in the thermal infrared channels. Further, in order that the reprocessing of the AVHRR data for the Pathfinder "benchmark" period (April 1987-November 1988) might commence in January 1993, only the behavior of the AVHRR on the NOAA-9 spacecraft (launch date: December 12, 1984), whose effective operational life would cover the "benchmark" period, would be addressed in these preliminary reports. However, the present report addresses non-linearity corrections to the thermal infrared measurements made by the AVHRRs on both NOAA-7 and NOAA-9 spacecraft as the work had been completed by the NOAA/NESDIS and University of Miami scientists who had been coopted for this task by the Chair of the AVHRR Pathfinder Calibration Working Group. A companion report addresses the behavior of the visible and near-infrared channels of the AVHRR on NOAA-9.

2. Nonlinearity corrections to thermal infrared measurements

2.1 General

The Mercury-Cadmium-Telluride (Hg-Cd-Te) detectors used in channels 4 and 5 of the AVHRRs exhibit non-linear response to incident radiation under certain conditions. This is illustrated in Figs. 1 and 2 (after Weinreb et al., 1990) which show pre-launch calibration data obtained in the laboratory; the variation of the response of a typical Hg-Cd-Te detector (in digital counts) used in channel 4 of the AVHRR on NOAA-9, while sensing the radiation from a laboratory blackbody whose temperature is varied over the range 205°K to 320°K in discrete steps, is shown in Fig. 1; it should be noted that the design of the electronic circuitry following the detector is such that the digital counts decrease with increasing values of incident radiation. The difference between the temperature of the blackbody and its brightness temperature, calculated from the radiance given by the linear fit of the data shown in Fig. 1, is shown in Fig. 2. The pattern of the residuals shown in Fig. 2 is typical of data with curvature (Weinreb et al., 1990). It is also apparent from Fig. 2 that nonlinearity errors can be of the order of a degree Celsius or larger as the blackbody temperature varies from about 200°K to 320°K. Since this temperature range encompasses the scene temperatures of interest to atmospheric, land, and ocean scientists, it becomes necessary to develop appropriate non-linearity correction algorithms for operational use.

Various non-linearity correction algorithms developed to date (e.g., Brown et al., 1985; Weinreb et al., 1990; Steyn-Ross et al., 1992) are based on the results of pre-launch calibration of the AVHRR in the thermal vacuum test chamber using the external blackbody, and the linear calibration using the radiances measured when the AVHRR looks at an internal calibration target (ICT) and space. It is thus assumed that the in-orbit performance of the instrument can be characterized in terms of the pre-launch calibration.

2.2 Pre-launch calibration of the AVHRR thermal infrared channels

We shall describe here briefly the pre-launch calibration of the thermal infrared channels of the AVHRR. The instrument is operated in the cross-track mode, simulating in-orbit operation, inside a thermal vacuum test chamber and views in succession an external blackbody source which simulates the Earth scene, the internal calibration target (ICT)-- a second blackbody source--mounted on the baseplate of the instrument, and a third blackbody maintained at liquid nitrogen temperature of 77°K to simulate cold space. The temperature of the external blackbody source is varied over the range 175 to 315°K, in 10°K steps from 175 to 290°K, and in 5°K steps from 290 to 315°K, to simulate the range of Earth scene temperatures. Similarly, the ICT temperature is generally varied over the range 10 to 20°C in 5°C steps to simulate the range of in-orbit operating temperature of the AVHRR; calibration of the instrument has been performed at higher values of the ICT temperature in some instances. It should be noted that the terms "ICT temperature," "base plate temperature," and "operating temperature" have been used interchangeably in the literature.

The calibration protocol calls for the measurement of the response of the AVHRR (in counts) when it views the external blackbody as its temperature is varied over the range mentioned above for each setting of the ICT temperature. The external blackbody temperature is monitored with a bank of 8 platinum resistance thermometers (PRTs), and that of the ICT with 4 PRTs; the calibration of the PRTs is traceable to standards maintained at the National Institute of Standards and Technology. The emissivity of the external blackbody is given as 0.996 and that of the ICT as 0.994 (e.g., ITT Aerospace/Optical Division, 1976); however, the emissivity of both is taken as unity in the computation of radiances sensed by the AVHRR from the "Temperature/Radiance" conversion tables; these tables list the radiances emitted by a blackbody within the passband of channels 4 and 5 of the AVHRR, at 0.1°K intervals over the temperature range mentioned above, as convolutions of the Planck function with the AVHRR's spectral response functions for the two channels (see Appendix A). Greater details of the design and construction of the various blackbodies and of the methods of monitoring the blackbody temperatures with the PRTs are found elsewhere (Brown et al., 1985; Weinreb et al., 1990).

2.3 Past, current, and proposed practices of nonlinearity corrections

We shall briefly review here the procedures adopted at NOAA to correct for nonlinearities in AVHRR channels 4 and 5. Past, current, and proposed practices will be illustrated with the help of Fig. 3 which is a schematic of the response of the AVHRR to incoming radiation. The curve ACS represents the nonlinear response-- in an exaggerated manner-- of the AVHRR, with radiance from space N_S assumed to be zero as indicated by the point S. The line AS represents the linear calibration obtained onboard from the

AVHRR signals when it views space and the internal calibration target (ICT) at any given temperature, say 20°C. The nonlinearity correction is given by the difference between the actual scene or target temperature derived (using the Planck equation) from the inversion of the true radiance N(C) corresponding to an AVHRR signal of C counts (obtained from the curve ACS), and the temperature derived from the inversion of the radiance N_{LIN} obtained from the linear calibration curve, AS. It should be noted that the nonlinearity corrections depend both upon the external blackbody (scene) temperature and the ICT temperature; the dependence on the ICT temperature was first pointed out by Brown et al. (1985) in the open literature.

The nonlinearity corrections can be minimized over any given range of scene temperatures by the use of linear calibrations as shown by the straight line AS' which uses a negative value N_S' for the radiance from space denoted by the point S'. It is also noticed in the laboratory calibration that the instrument response, the curve ACS, has a weak but finite dependence on the ICT temperature itself, the dependence ranging from about 2 counts to 10 counts as the ICT temperature varies from 10°C to 20°C, with the larger disparities being noticed at the higher scene temperatures; this results in the curve ACS shifting to the right with increasing temperatures of the ICT.

It had been the practice in NOAA till the mid-80s to use the concept of "negative radiance from space" as indicated by the point S' in Fig. 3 to minimize the magnitude of the nonlinearity errors over a limited temperature range, and to furnish a single set of nonlinearity errors in tabular form for an ICT temperature of 10°C. For NOAA-9, two sets of values were furnished, one corresponding to $N_S = 0$, and the other with a negative value of radiance from space, N_S'; the temperature errors associated with $N_S = 0$ were provided for purposes of information only, and were not intended to be used in correcting the nonlinearities. There have been considerable revisions in the procedures of estimating the nonlinearity corrections starting with the AVHRR on NOAA-10, following the findings of Brown et al. (1985) and Weinreb et al. (1990) which will be briefly described.

Brown et al. (op cit) demonstrated from a careful analysis of the pre-launch thermal vacuum test data furnished by ITT Aerospace/Optical Division, Fort Wayne, Indiana--who designed and built the AVHRR-- that it was necessary to evaluate nonlinearity corrections for different values of the ICT temperature; they also drew attention to some inconsistencies in the procedures followed at NOAA until the mid-80s. Their findings were based on using the linear calibration obtained from the laboratory measurements of the ICT and the space-view target maintained at 77°K. Weinreb et al. (op cit) argued that it was necessary that the in-orbit calibration of the AVHRR should be traceable to the calibration of the external blackbody used in the pre-launch calibration, and thence to NIST standards. They stipulated that the calibrations of the ICT and the laboratory blackbody should be consistent; thus, (a) the radiance of the ICT computed from the temperature measurements of the embedded PRTs should be identical to the radiance measured by the AVHRR itself after it had been calibrated against the external blackbody; and (b) the AVHRR should put out the same signal (in counts) when the temperature of the ICT, as measured by the embedded PRTs, equalled the temperature of the external blackbody. This would imply that the nonlinearity correction should vanish when the ICT and external blackbody temperatures are the same. However, analysis of the thermal vacuum test data showed these conditions were not always satisfied, with the differences in the derived radiances translating to brightness temperature differences of the order of 0.7°C. The calibrations of the PRTs embedded in the ICT were suitably modified to satisfy the consistency conditions mentioned above, and tables of non-linearity corrections were generated for the AVHRRs on NOAA-9, and on the spacecraft that followed, corresponding to nominal ICT temperatures of 10, 15, and 20°C, for scene temperatures ranging from 205°K to 320°K; these look-up tables are currently in use in NOAA.

The use of these look-up tables entails two-dimensional interpolation in the Earth scene temperature, and in the ICT temperature. When the ICT (or the AVHRR operating temperature) exceeds the largest value of the ICT for which the correction table has been generated, the tabulated values have to be extrapolated; this may lead to erroneous values of nonlinearity corrections. In addition, instrumental noise and measurement errors inherent in the pre-launch data are projected into the in-orbit data.

It was also noted by Weinreb et al. (op cit) in the course of their investigation that the curves of correction terms versus temperature for the three ICT or baseplate temperatures were nearly parallel; hence, they pointed out that, if these curves were exactly parallel to one another, it might be possible to express the nonlinearity correction as a simple function of the difference between the scene and ICT temperatures, thereby rendering the correction term independent of the ICT temperature. To eliminate the use of look-up tables of nonlinearity corrections with the attendant ambiguities, Brown et al. (1993) have recently proposed that the temperature nonlinearity corrections should be expressed as a quadratic function of the difference between the scene temperature, obtained from the linear calibration based on measurements of the ICT and space radiances (graph AS of Fig. 3), and the ICT temperature. It is also stipulated that the correction should vanish when the scene temperature is the same as the ICT temperature. This procedure will be referred to as the "MIAMI" method hereafter for convenience.

Walton et al. (1993) have proposed that the nonlinearity corrections should be expressed in terms of radiance which is the physical quantity that is actually measured by the AVHRR. Also, the need for corrected radiances is felt keenly in the generation of several atmospheric, land, and ocean products (e.g., Steyn-Ross et al., 1992). Corrected scene temperatures can be derived from the corrected radiances with the use of "Temperature/Radiance" conversion tables mentioned in Section 2.2. They propose expressing the radiance correction as a quadratic function in a pseudo-linear radiance, N_{LIN}", obtained from the linear calibration based on the measurement of the radiance from the ICT at a known temperature and an optimized, negative value of the radiance from space. N_S" (graph AS" of Fig. 3). The basic difference between the optimized, negative value of radiance from space which has been presently proposed and the negative radiance from space, N_S', that has been used to date is the manner in which the two are evaluated. The

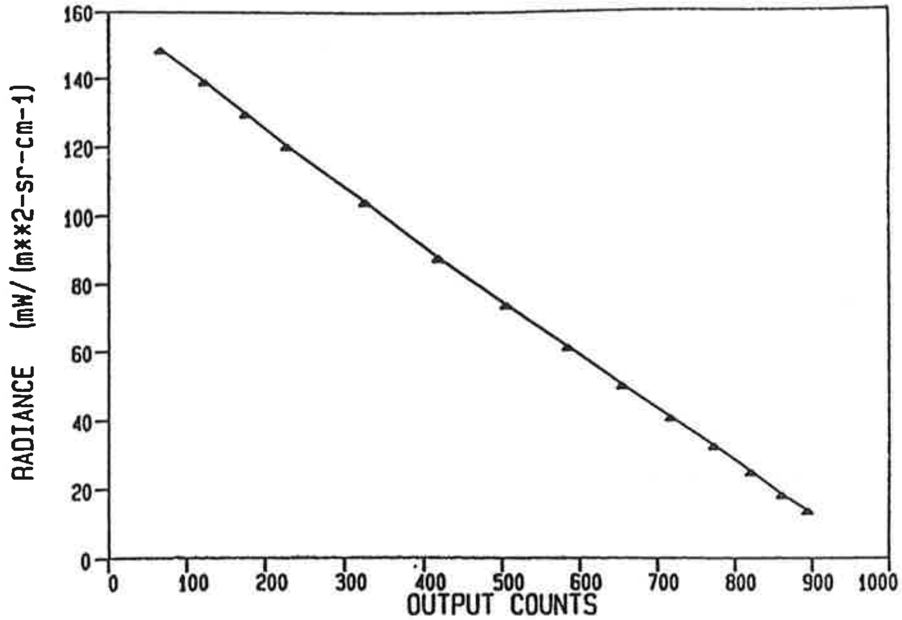


Figure 1. Calibration curve for channel 4 of NOAA 9 AVHRR.

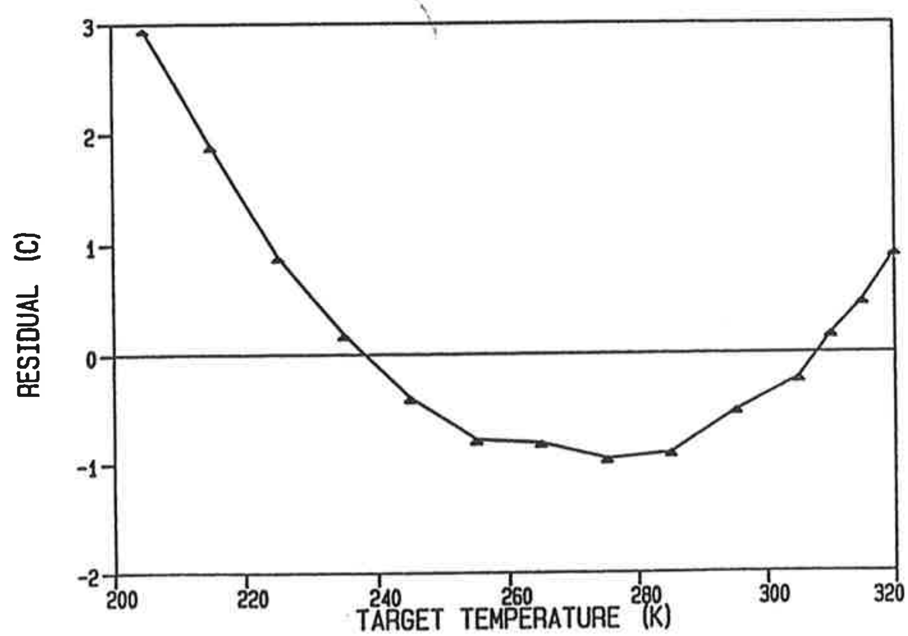


Figure 2. Residuals from linear fit to calibration curve in Figure 1.

(after Weinreb et al., 1990)

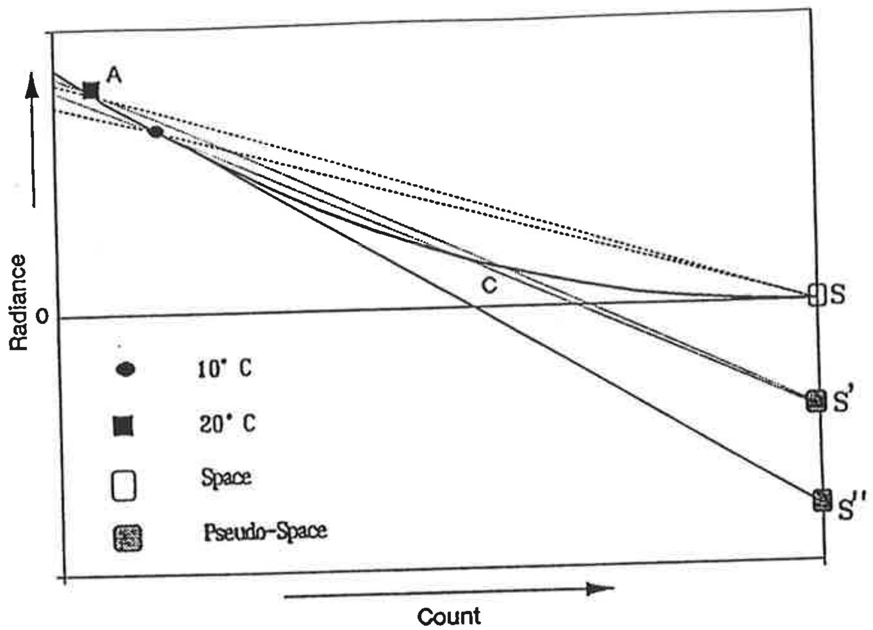


Figure 3. Schematic of the variation of the AVHRR response in counts with incident radiation.

technique of determining the optimized, negative value of radiance from space will be described in the next section. We shall refer to this method as the "NESDIS" method for convenience hereafter. A very basic description of this procedure is found in Rao et al. (1993).

3. Comparison of the MIAMI and NESDIS methods

3.1 General

It was decided at the AVHRR Pathfinder Calibration Working Group meeting of October 5-6, 1992, and at the meetings that followed between the University of Miami and NOAA/NESDIS groups, that the Miami and NESDIS methods of expressing the nonlinearity corrections in the form of simple formulae would be tested on a set of pre-launch, thermal vacuum test data that would be assembled by the University of Miami group, and adjusted by the NESDIS group to handle the inconsistency between the calibrations of the ICT and the laboratory blackbody (see Section 2.3). The adjustment consisted of the following steps:

(1) Derive the temperature of the ICTs from the internal PRTs;
(2) Convert this temperature to radiance using the "Temperature/Radiance" conversion table;
(3) Using the radiance determined in step (2) above, derive a simulated ICT count response from the external blackbody count/radiance curve and apply it for linear calibration.

It was agreed that this procedure of adjustment of ICT data would be followed for all of the thermal infrared channels on the different AVHRRs in operation during the Pathfinder period. Further, the pre-launch calibration data for the AVHRR on NOAA-7 would be used primarily in this comparison since the test data had been obtained at nominal ICT temperatures of 10, 15, 20, 25, and 30°C which would permit part of the data to be used to develop the correction formulae or algorithms, and the rest to be used as independent data to test the algorithms. It was decided to use the test data at ICT temperatures of 10, 15, and 20°C to develop the correction algorithms, and use the same to fit the pre-launch test data at 25 and 30°C ICT temperatures. Closeness of fit between the measured temperatures of the external blackbody and the derived values, after the corrections had been applied, and the absence of trends, would be used as criteria to evaluate the relative merits of the two methods.

The MIAMI method expresses the temperature correction as:

$$\Delta T = a + b(T_{LIN} - T_{ICT}) + c(T_{LIN} - T_{ICT})^2 \tag{1}$$

and the NESDIS method gives the radiance correction as:

$$\Delta N = a' + b'(N''_{LIN}) + c'(N''_{LIN})^2 \tag{2}$$

where N_{LIN}'': the linear radiance corresponding to an AVHRR signal of C counts, obtained from the linear calibration AS" (Fig. 3) based on the optimized, negative radiance from space,

T_{LIN}: scene temperature from the linear calibration AS of Fig. 3; and

T_{ICT}: temperature of the internal calibration target.

Temperatures are expressed in °K, and radiances in units of mW/ (m^2 sr cm^{-1}).

Before we proceed to a discussion of the results obtained in this comparison, the method of determining the optimized, negative radiance from space used in the NESDIS procedure will be described. Referring to Fig. 3, let the straight line AS" denote the linear calibration with the optimized, negative radiance from space-- the point S". The point A moves along the curve ACS depending upon the ICT temperature. It can be shown that the linear radiance, N_{LIN}'', corresponding to AVHRR-measured signal of C counts is given by:

$$N''_{LIN} = N_{ICT}\frac{(C_S - C)}{(C_S - C_{ICT})} + N''_S\frac{(C_{ICT} - C)}{(C_{ICT} - C_S)} \tag{3}$$

where C_{ICT}, C_S: measured counts when the AVHRR views the ICT and space respectively;

and N_{ICT}, N_S'': ICT radiance and the optimized negative radiance from space respectively.

Our objective is to find a value of N_S'' that would enable us to express the nonlinearity corrections in terms of a simple formula at all ICT temperatures. Let us denote by $N_{NLIN}(C_n,T_{ICT})$ the nonlinear radiance correction, i.e., the difference between the radiances from ACS and AS" of Fig. 3, when the AVHRR views the external blackbody at temperature T_n and yields counts C_n while the ICT is at temperature T_{ICT}. We stipulate that the optimum value of N_S'' should minimize the quantity

$$\begin{aligned} \sum & [N_{NLIN}(C_n,10) - N_{NLIN}(C_n,15)]^2 \\ & + [N_{NLIN}(C_n,10) - N_{NLIN}(C_n,20)]^2 \\ & + [N_{NLIN}(C_n,15) - N_{NLIN}(C_n,20)]^2 \end{aligned} \qquad (4)$$

The summation is carried over the number n of discrete values of temperature above 200°K at which the external blackbody is maintained during the thermal vacuum test. It is apparent that we have used the pre-launch calibration data at the three ICT temperatures of 10, 15, and 20°C.

The optimum value of N_S'' has been determined by iteration on a computer. At this optimum value of N_S'', the non-linearity corrections at all three ICT temperatures are very close to one another; thus, a single set of values for a', b', and c' (see Eqn. 2) would be adequate.

3.2 Results of the comparison of the MIAMI and NESDIS methods of nonlinearity corrections

In the MIAMI method, the non-linear temperature correction is added to the linear temperature estimate to produce an estimate of the external target temperature. This estimate is subtracted from the measured external blackbody (target) temperature, which gives a temperature difference. There are M temperature differences for the AVHRR on a given satellite; M is the number of valid data points whose maximum value is equal to the product of the number of external blackbody temperature settings and those of the internal calibration target. The M differences are squared, summed, the sum divided by (M-3), and a square root taken. This is the RMS difference used in the comparisons.

In the NESDIS method, the nonlinear radiance correction is added to the linear radiance obtained from the graph AS" of Fig. 3 to produce an estimate of the external blackbody radiance. To compare the NESDIS method with the MIAMI method, the radiance estimate is then converted to a temperature estimate via the "Temperature/Radiance" conversion tables. This estimate is then subtracted from the measured external blackbody (target) temperature to give a temperature difference. The RMS difference for this method is then computed the same way it was done for the MIAMI method. Table 1 lists the RMS differences (°K) between the pre-launch external target temperatures, and fitted temperatures by the two methods. It is apparent that both methods reproduce the measured data very accurately. The two methods yield smaller RMS differences for the channel 5 data on the two spacecraft. They reproduce the NOAA-9 data about equally well. It is only for the NOAA-7 data that the results from the two methods differ appreciably.

Table 1. Root-mean-square differences (°K) between pre-launch external target temperatures and fitted temperatures computed by each of the two correction methods.

	Channel 4		Channel 5	
	NOAA-7	NOAA-9	NOAA-7	NOAA-9
NESDIS	0.107	0.174	0.088	0.156
MIAMI	0.217	0.203	0.156	0.163

Note: The total number of data points is 67 for both channels of the AVHRR on NOAA-7, and 39 for both channels of the AVHRR on NOAA-9.

The nonlinear corrections given by the two methods are shown in Fig. 4 along with the original thermal vacuum test data (middle graph). For purposes of comparison, and to conform to earlier work (e.g., Brown et al., 1985; Weinreb et al., 1990), these corrections have been computed with respect to the linear estimates corresponding to zero radiance from space-- the graph AS of Fig. 3. The results from the NESDIS method are shown in the bottom panel of Fig. 4. The curves in this graph closely resemble the curves based on the measured corrections (middle panel) but the irregularities due to noise have been smoothed out. The top panel shows the results obtained with the MIAMI method. For high external target temperatures, these corrections are obviously a smoothed version of the measured corrections. However, at temperatures of 250°K and below, the non-linear corrections from this (MIAMI) method depart substantially from those computed using the measured data. The behavior of the MIAMI method does not appear to be caused by any peculiarities in the NOAA-7 pre-launch calibration data set.

Figures 5 and 6 show that the NESDIS method reproduces the measured pre-launch external target temperature data for ICT temperatures of 25°C and 30°C very well for channels 4 and 5 of the AVHRR on NOAA-7. The (measured - fitted) temperature differences at these ICT temperatures are connected in the figures by the dashed and solid lines. Estimates from the MIAMI method are accurate in the 250-320°K external temperature range, but not nearly as accurate below 250°K. This is true for both channels. Similar results are shown for the two channels of the AVHRR on NOAA-9 in Figs. 7 and

8. The MIAMI method introduces relatively large biases at the lower scene temperatures with the NOAA-7 data when the ICT temperature is either 25°C or 30°C; there are not any obvious peculiarities about the NOAA-7 data that would explain this behavior.

We have reason to believe that the pre-launch thermal vacuum calibrations of the AVHRR on NOAA-9 were flawed; there is evidence for this in Fig. 9 where the nonlinearity corrections for channel 5 based on the calibration results are shown. The cross-over of the curves corresponding to the three ICT temperatures, especially at the higher scene temperatures, is noticeable; this cross-over is in contrast to the relatively smooth variation of the nonlinear corrections with scene temperature observed with the two channels of the AVHRR on NOAA-7 (e.g., the middle panel of Fig. 4). To minimize the impact of the flawed calibration, we have eliminated from consideration the pre-launch calibration data inside the boxes in the determination of the values of the coefficients a', b', and c' (Eqn. 2); this modified data will be referred to as the "edited" data.

We have shown in Fig. 10 the radiance-based (NESDIS) nonlinearity corrections as a function of external target temperature for channel 5 of the AVHRR on NOAA-9; the "edited" data have been used in these computations. The dependence of the nonlinearity corrections on the ICT temperature is once again apparent in the data displayed; this dependence would have effectively vanished had we used the unedited data. Similar results are obtained for channel 4.

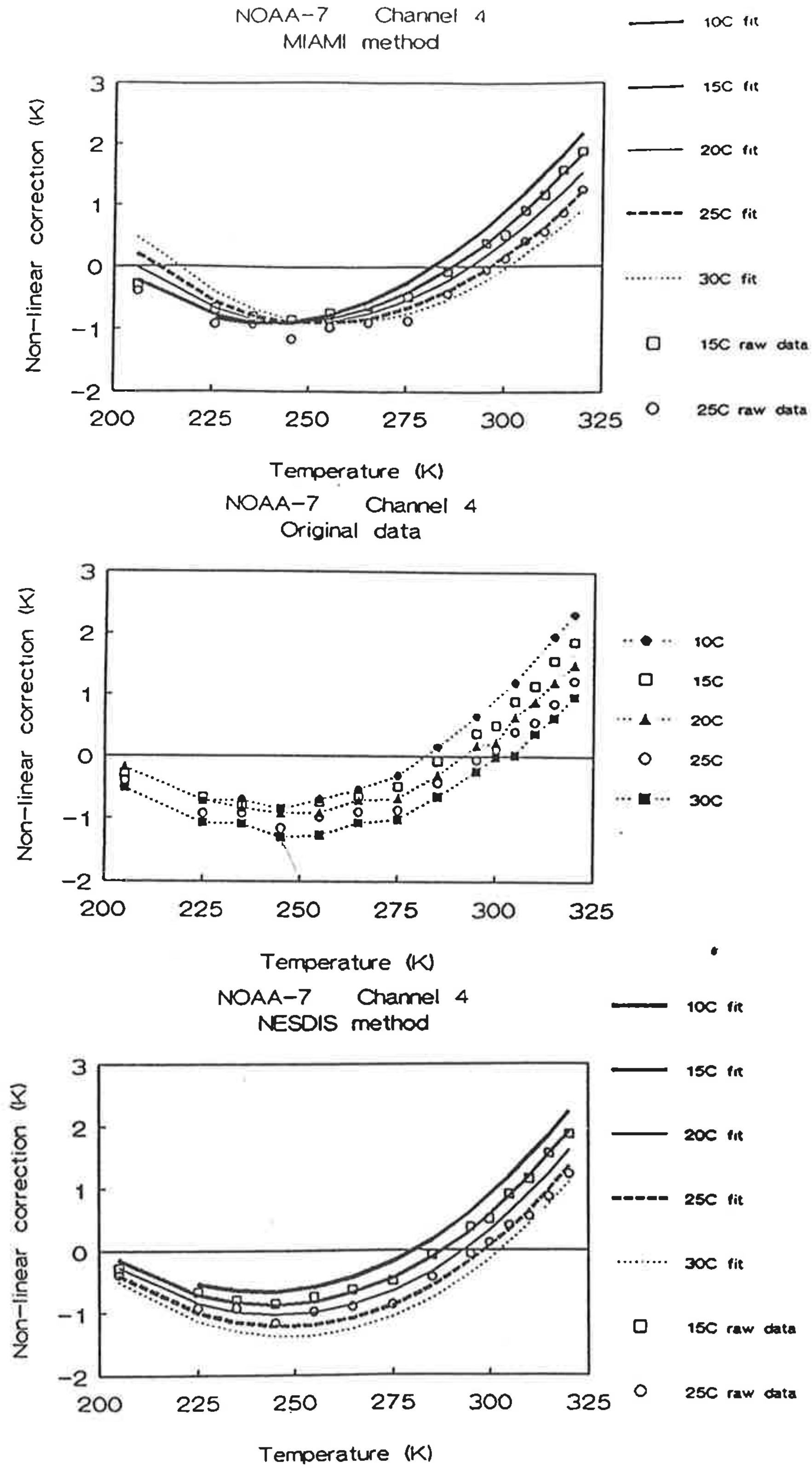


Figure 4. Non-linear temperature corrections plotted as a function of external target temperature for measured pre-launch data (middle panel), for data from the MIAMI method (top panel), and for data from the NESDIS method (bottom panel)

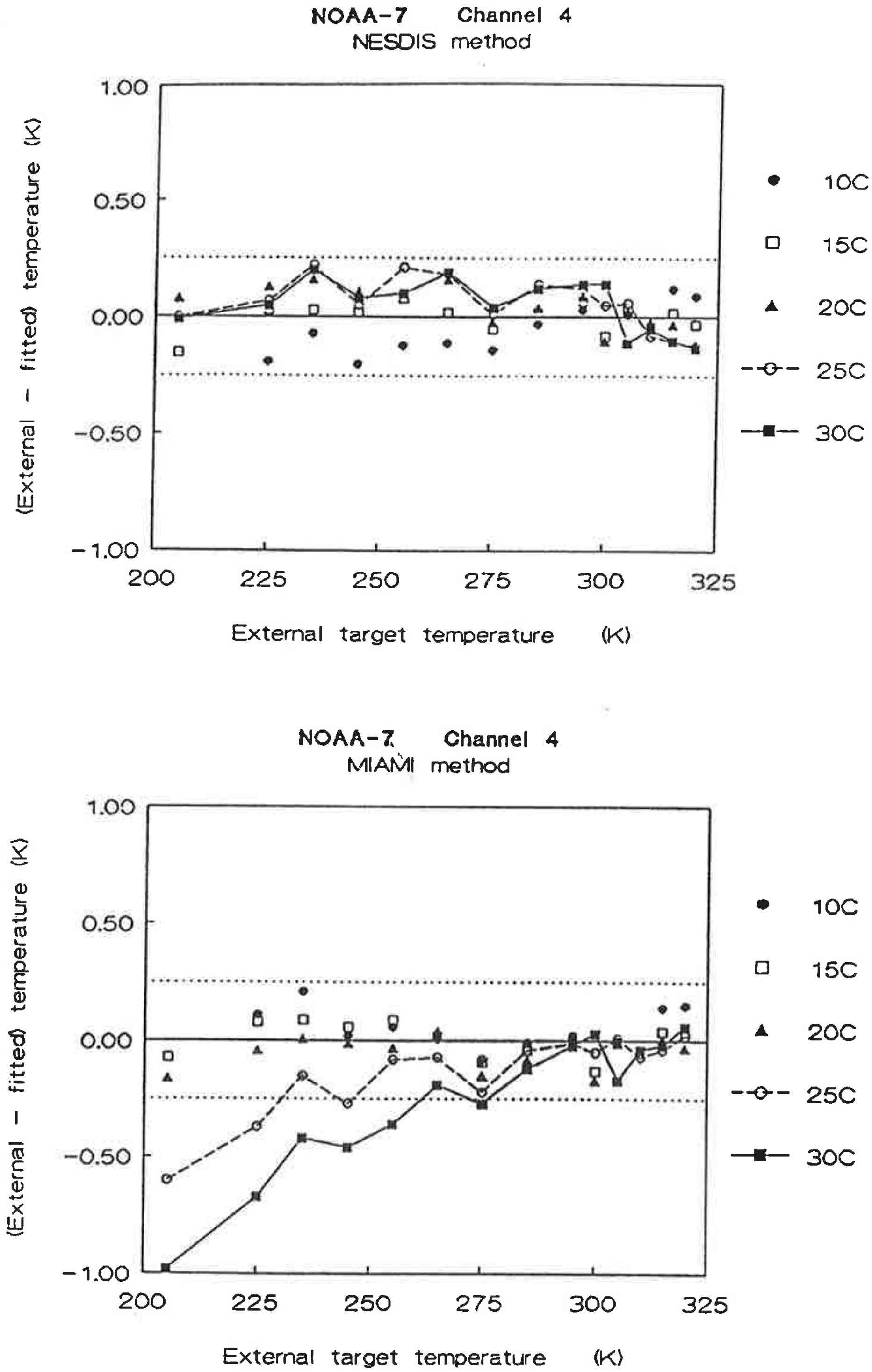


Figure 5. (Measured - fitted) temperature differences for all internal target temperature settings, using NOAA-7 channel 4 data for both the MIAMI and NESDIS methods.

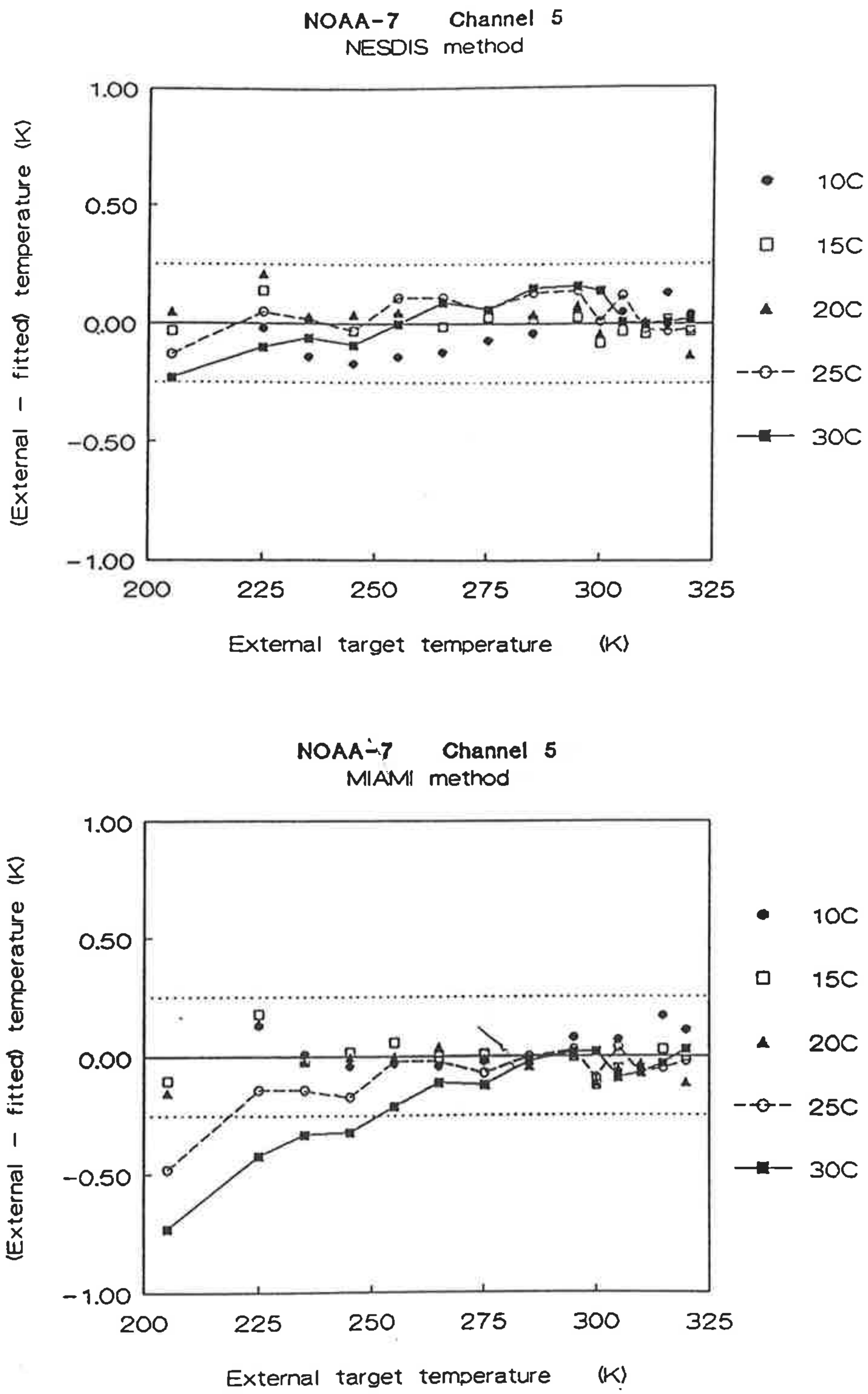
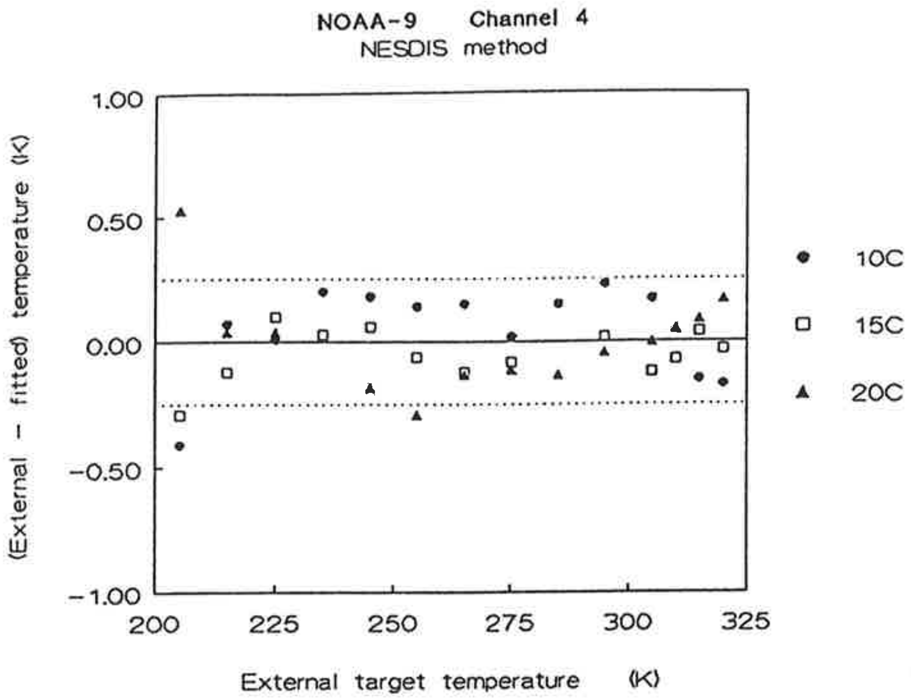


Figure 6. (Measured - fitted) temperature differences for all internal target temperature settings, using NOAA-7 channel 5 data for both the MIAMI and NESDIS methods.



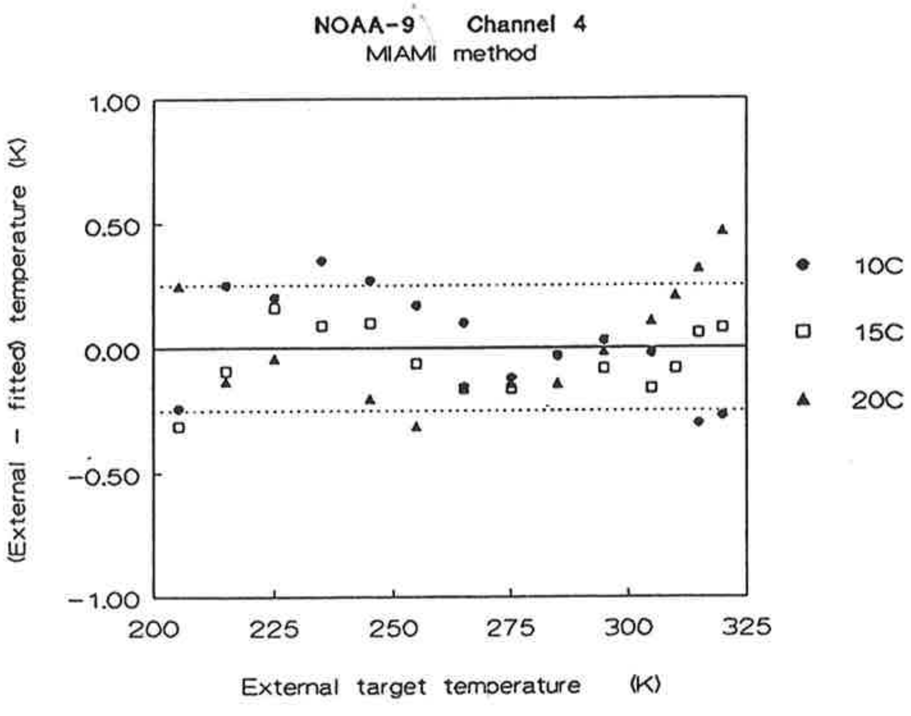
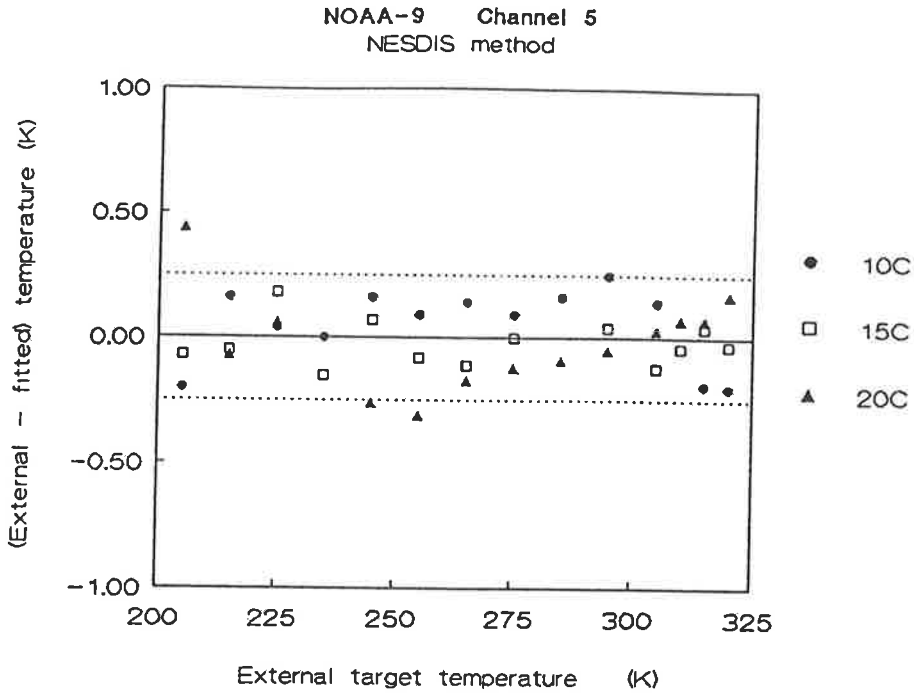


Figure 7. (Measured - fitted) temperature differences for all internal target temperature settings, using NOAA-9 channel 4 data for both the MIAMI and NESDIS methods.



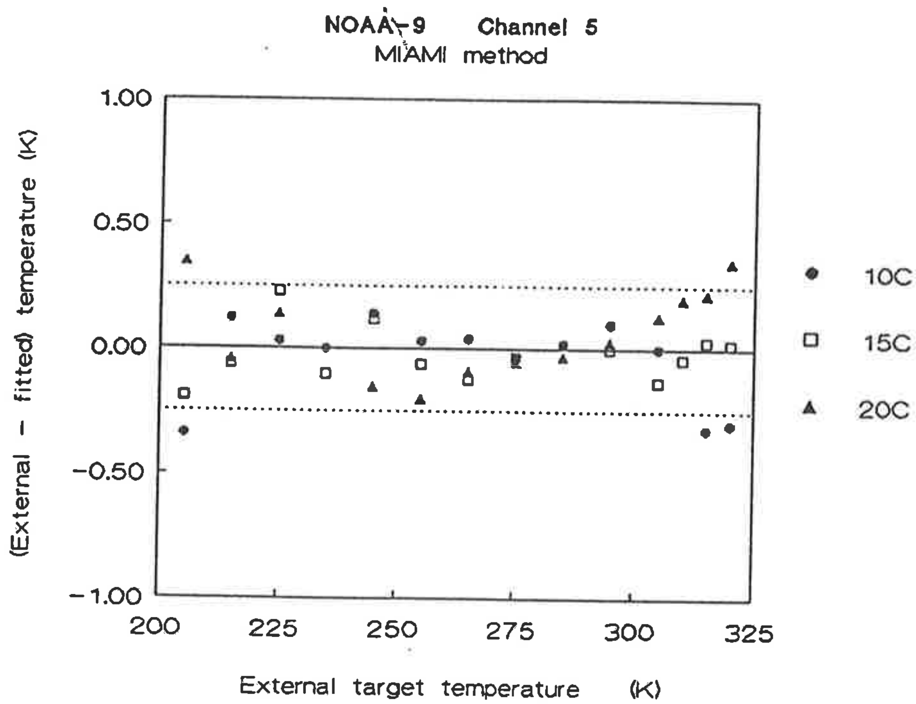


Figure 8. (Measured - fitted) temperature differences for all internal target temperature settings, using NOAA-9 channel 5 data for both the MIAMI and NESDIS methods.

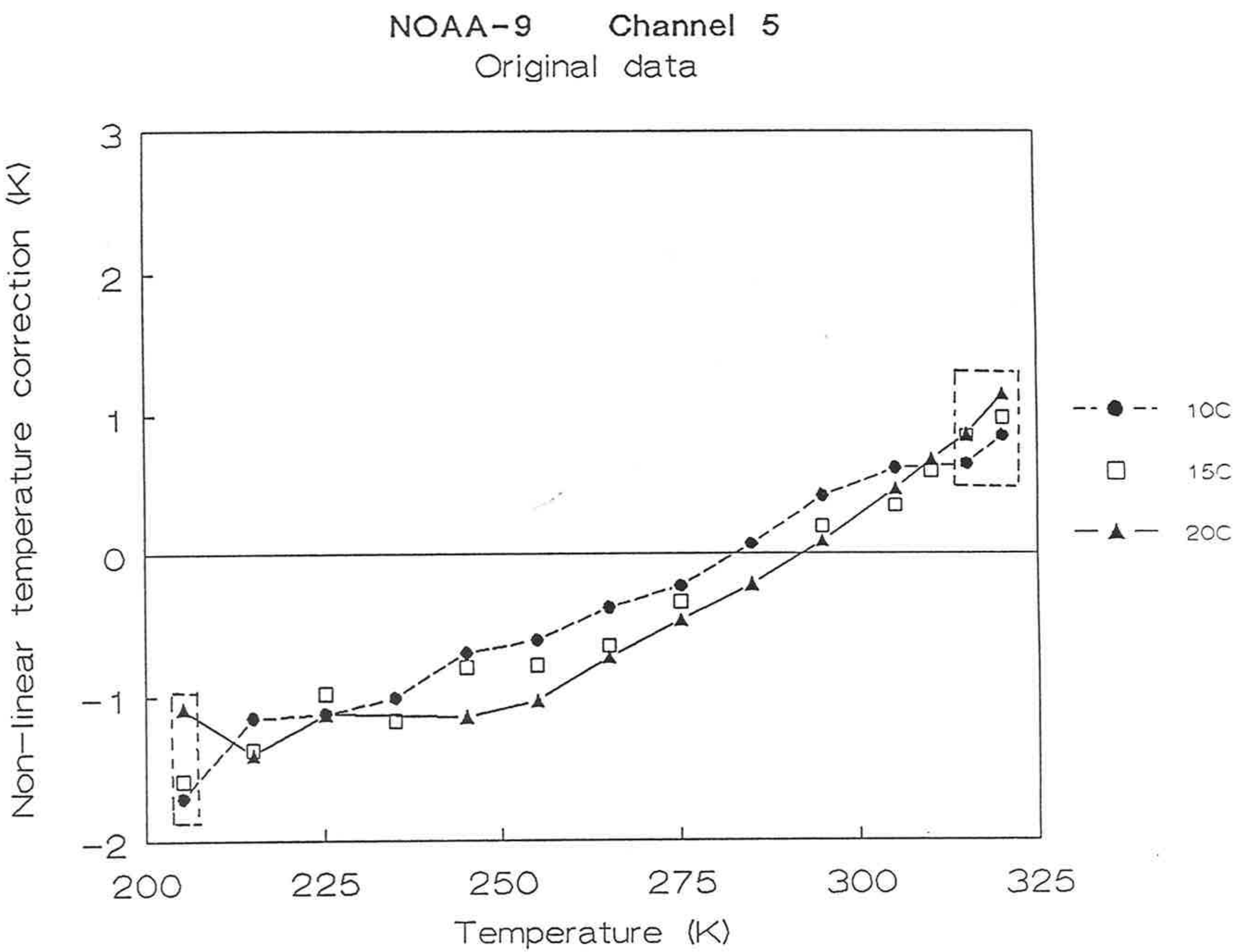


Figure 9. The original pre-launch calibration data for channel 5 of the AVHRR on NOAA-9.

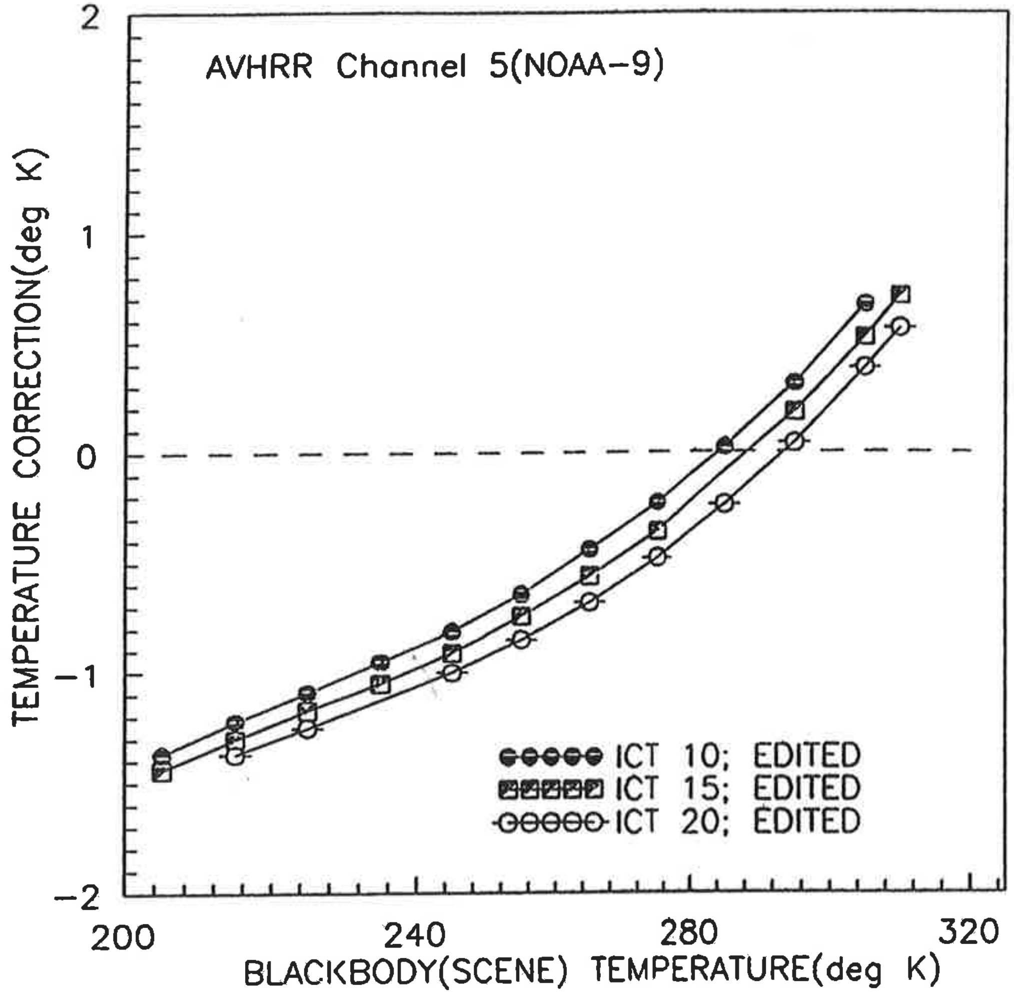


Figure 10. Non-linearity corrections for channel 5 of the AVHRR on NOAA-9 (the edited data have been used)

In summary, the results of the comparison are:

a. Both methods reproduce the original measured data accurately, with RMS differences between measured and fitted data on the order of 0.1-0.2°K. In the 275-310°K sea surface temperature range, the temperature differences are even smaller.

b. The NESDIS method has slightly lower RMS differences for both channels on both satellites.

c. The biases in the fits are not a large problem.

d. The NESDIS method extrapolates better for the NOAA-7 25°C and 30°C internal target temperature data.

e. The NESDIS method yields better agreement with observations at lower scene temperatures.

It should be recognized that the present work was directed towards developing simple nonlinearity correction procedures that would account for the nonlinearities observed in the laboratory (see middle panel of Fig. 4) over the entire range of scene temperatures to the best extent practicable. Accordingly, the above results, based on the pre-launch calibration of the AVHRRs, have been used as the bases for the recommendations made in the next section for the implementation of the nonlinearity corrections. It is thus assumed that the pre-launch behavior of the instrument is a faithful description of its post-launch performance.

4. Recommendations

Based on the above results, independently arrived at by the University of Miami and NESDIS scientists, it is recommended that the NESDIS nonlinear correction method be adopted to calibrate the AVHRR infrared data as its performance is equal to or better than that of the University of Miami nonlinear correction method over the entire range of scene temperatures encountered by the AVHRR.

The radiance-based quadratic formula given below yields the **corrected radiances**:

$$N = A(N''_{LIN}) + B(N''_{LIN})^2 + C \tag{5}$$

The coefficients A, B, and C are determined from the pre-launch test data by fitting a curve to the differences between the actual radiance obtained from the curve ACS of Fig.3 and the radiance obtained from the linear calibration AS" using conventional regression techniques; they are listed below in Table 2, along with the values of N_S'', for channels 4 and 5 of the AVHRRs on NOAA-7 and -9 spacecraft.

The pseudo-linear radiance N_{LIN}'' corresponding to counts C is given by:

$$N''_{LIN} = G''C + I'' \tag{6}$$

The gain G" is given by:

$$G'' = G' \frac{N_{ICT} - N''_S}{N_{ICT} - N'_S} \tag{7}$$

where G' and N_S' are respectively the gain and radiance from space; G' values are found in the 1B data; N_S' values are listed in Table 3; and have been used operationally to derive G' and I'.

The intercept I" is given by:

$$I'' = N''_S - \frac{G''}{G'}N'_S + \frac{G''}{G'}I' \tag{8}$$

I' values are found in the 1B data.

The method of computing N_{ICT} using the PRT information in the 1B data and the "Temperature/Radiance" conversion tables is described in Appendix A; the same conversion tables can also be used to determine the correct brightness temperatures from the radiances given by Eqn. 5. The conversion tables may be obtained from NOAA/NESDIS or can easily be generated by the user.

Table 2. Values of A,B,C, and N_S''

	NOAA-7 Channel 4	NOAA-7 Channel 5	NOAA-9 Channel 4	NOAA-9 Channel 5
A	0.89783	0.93683	0.88643	0.95311
B	0.0004819	0.0002425	0.0006033	0.0002198
C	5.25	3.93	5.24	2.42
N_S''	-5.16	-4.28	-5.53	-3.06

Note: Radiances are in units of $mW/(m^2\ sr\ cm^{-1})$. The entries for the two channels of the AVHRR on NOAA-9 are based on the edited, pre-launch thermal vacuum test data.

Table 3. N_S' values for the AVHRRs on NOAA-7 and -9 spacecraft

NOAA-7 Ch.4	NOAA-7 Ch.5	NOAA-9 Ch.4	NOAA-9 Ch.5	Period of Validity
-1.176	-1.346			Entire Life
		-3.384	-2.313	12-12-84 to 9-30-86
		0	0	9-30-86 to 11-7-86
		-3.384	-2.313	11-7-86 to 10-16-87
		0	0	10-16-87 to present

Acknowledgment:

The work reported here was supported by the Information Management Component (NOAA Pathfinder Program Manager: Dr. Arthur Booth) of the Climate and Global Change Program, NOAA Office of Global Programs. Useful discussions with Dr. Michael Weinreb, NOAA/NESDIS Satellite Research Laboratory, are herewith acknowledged.

APPENDIX A: Implementation of the radiance-based nonlinearity correction method in the Pathfinder program

a. Calculation of G"

In addition to using the quality control functions which are already imbedded in the 1B calibration data, the Pathfinder calibration activity should try to improve upon them based on past operational experience. The nonlinearity corrections must be accurate over the entire range of terrestrial temperatures and be computed in a consistent manner for all the AVHRR/2 instruments.

The method of utilizing the quality-controlled calibration information that already exists in the 1B data to generate the gain or slope of the curve AS" of Fig. 3 will be described here. Let us assume for now that the output of each thermal channel (in counts) is a linear function of sensed radiance. The equation N = GC + I describes the relationship between counts and radiances: N is the radiance of the target at count value C; G is the channel gain; and I is the intercept. The gain of each channel is calculated by (e.g., Lauritson et al., 1979):

$$G = \frac{N_S - N_{ICT}}{C_S - C_{ICT}} \tag{A1}$$

N_s is the radiance of space, N_{ICT} is the radiance of the internal calibration target (ICT) and C_S and C_{ICT} are the mean output count values when the instrument views space and the ICT, respectively. The intercept of each channel is calculated by:

$$I = N_S - GC_S \tag{A2}$$

As mentioned earlier, until the mid-80s, nonlinearity corrections of different degrees of sophistication have been applied to the temperatures derived from the linear calibration described above.

For the Pathfinder effort an optimized, negative radiance of space parameter has been introduced in order to simplify the process of correcting for the nonlinearity of the relationship between counts and radiances in channels 4 and 5 (channel 3 is taken to be linear in its response). The optimized, negative radiance of space which will be used in the recommended procedure is such that it renders the coefficients of the quadratic correction equation in N_{LIN}" independent of the ICT temperature. However, because this parameter will be different from the values of radiance from space used before or since 1986, the calibration coefficients imbedded in the 1B data stream for each channel and each satellite will have to be adjusted. This adjustment, as well as the nonlinearity correction, should be transparent to data users.

The gains G" and G' obtained from the linear calibrations AS" and AS' of Fig. 3 are given by:

$$G'' = \frac{N_S'' - N_{ICT}}{C_S - C_{ICT}}; \qquad G' = \frac{N_S' - N_{ICT}}{C_S - C_{ICT}} \tag{A3}$$

Thus, the gain G" can be derived from the gain G' and radiance from space N_S' from the following relationship:

$$G'' = G' \frac{(N_S'' - N_{ICT})}{(N_S' - N_{ICT})} \tag{A4}$$

G' is part of the 1B data; Table 3 (main text) lists N_S' values. In a similar manner, the intercept I" can be derived from the imbedded value I', using the expressions for I' and I" from Eqn. A2; this yields Eqn. 8 (main text).

It was assumed in the derivation of expressions for G" and I" (Eqns. 7 and 8 of main text) that the user has all of the 1B telemetry information including the PRT measurements of the internal calibration target which are needed for the calculation of N_{ICT}. Users who may not have access to the ICT temperature (PRT) data have to base their calculation of N_{ICT} on estimated values of the ICT temperature lying within the range of the normal operating temperature of the AVHRR. We have examined the effects of using estimated values of the ICT temperature on the derived values of G" and I" and on N_{LIN}" for channel 4 of the AVHRR on NOAA-11 spacecraft --the worst case scenario-- using the readily available data. The results are summarized in Table A1 below.

The entries in Table A1 correspond to two different values of N_S", -5 and -10 which cover the greater part of the range of N_S" values we may encounter, and a single value of N_S', 0. Three nominal values of the ICT temperature, 15, 20, and 25°C, have been used, and the values of G", I", and N_{LIN}" (labelled linear radiance in the table) for four different count values have been calculated. For purposes of illustration, let us take the ICT temperature to be 20°C when it was actually 15 or 25°C. We see from the entries in Table A1 that errors of the order of 0.5% will be made in the various parameters of interest, and these errors in turn will lead to comparable errors in the corrected radiances and retrieved temperatures; channel 5 should behave in a similar manner.

It should be noted that G' and I' values imbedded in the 1B data are to be modified or altered to yield G" and I" only if the "optimized" radiance of space is different from that used to generate them. The larger this radiance of space difference, the greater the correction and the greater the possible error if the ICT temperature is not known.

b. Quality control

In operational practice, a calibration block consists of 50 scan lines of 1B data. This amount of data is needed to quality control the individual platinum resistance thermometer (PRT) measurements of the ICT temperature with gross filtering and outlier rejection checks (two sigma filtering). However calibration coefficients are computed with each set of 5 scan lines (a sub-block), with each scan line providing 10 ICT and space readouts. This sub-block of data (50 pixels) is sufficient to apply the two sigma filtering (rejection of pixel count values which differ from the mean by more than two standard deviations) to the infrared channel measurements of the ICT and space. These filtering procedures should be retained for AVHRR Pathfinder processing and are already included in the gain calibration coefficients imbedded in the 1B data. Further details of the format of the calibration information in the 1B data is given in Lauritson et al. (1979). For Pathfinder processing, an additional quality control of the correction to the gain coefficient described by Eqn. A4 is needed. This correction can be computed with a sub-block of 1B data using the mean of one measurement from each of four PRTs to determine the radiance of the ICT as described in the following section. If the individual PRT measurements do not agree to within one degree Celsius of each other, the mean from the previous sub-block may be used (Fortunately, errors in the computation of N_{ICT} tend to dampen out when applied in Eqn. A4.)

What is lacking during operational processing is a consistency check between the PRT measurements and the AVHRR response when viewing the ICT. Inconsistency can result if the temperature of the ICT changes rapidly or if sunlight impinges directly onto the ICT or if the instrumental noise becomes excessive. As a check for consistency, a range for the values that can be assumed by G' should be provided for different periods in the operational life of the instrument. G' will normally be computed in two different ways: first, the data within one sub-block will be used to define a high resolution value for the gain parameter; next, the previous ten good quality sub-blocks of data will define a low resolution value for the parameter G'. If within a given sub-block the high resolution value of the parameter G' falls outside the specified range, then the user will be supplied with the lower resolution parameter associated with this sub-block of data. This procedure could be applied to each channel separately, but may only be necessary for channel 3 because of its sensitivity to the effects of occasional exposure of the ICT to sunlight.

Table A1. Gain, intercept, and linear radiance for different ICT temperatures

	Ns" = -5; Ns' = 0			Ns" = -10; Ns' = 0		
ICT Temperature	15	20	25	15	20	25
ICT Radiance	93.5	101.3	109.4	93.5	101.3	109.4
Gain in 1B(G')	-0.1736	-0.1736	-0.1736	-0.1736	-0.1736	-0.1736
Corrected Gain(G")	-0.1825	-0.1819	-0.1813	-0.1922	-0.1907	-0.1895
Intercept in 1B(I')	172.4	172.4	172.4	172.4	172.4	172.4
Corrected Int(I")	176.2	175.6	175	180.8	179.4	178.2
Linear radiance (cnts=200)	139.7	139.2	138.7	142.4	141.3	140.3
Linear radiance (cnts=400)	103.2	102.8	102.5	103.9	103.1	102.4
Linear radiance (cnts=600)	66.7	66.5	66.2	65.5	65	64.5
Linear radiance (cnts=800)	30.2	30.1	30	27	26.8	26.6

Note 1. Radiances are in units of $mW/(m^2\ sr\ cm^{-1})$

Note 2. ICT temperatures are in deg C.

c. Computation of Internal Calibration Target (ICT) radiances

To calculate the ICT radiance N_{ICT}, it is first necessary to compute the internal target temperature. The conversion of PRT mean counts to temperature uses the following:

$$T_i = \sum_{j=0}^{4} a_{ij} X_i^j \tag{A5}$$

where X_i is the mean count for PRT_i where i = 1,2,3,4; a_{ij} are the coefficients of the conversion algorithm and T_i is the temperature of the internal target calculated from PRT_i. The coefficients a_{ij} are supplied by the instrument manufacturer (ITT Aerospace/Optical Division, Fort Wayne, Indiana). The average temperature of the internal target is computed by

$$T = \sum_{i=1}^{4} b_i T_i \tag{A6}$$

where T is the average of the ICT temperatures and b_i is the weighting factor for each PRT.

The radiance N sensed in a particular channel from a blackbody at temperature T is the weighted mean of the Planck function over the spectral response function of the channel; i.e.,

$$N(T) = \frac{\int_{\nu_1}^{\nu_2} B(\nu, T)\, \phi(\nu)\, d\nu}{\int_{\nu_1}^{\nu_2} \phi(\nu)\, d\nu} \tag{A7}$$

where ν is wavenumber (cm^{-1}), $\phi(\nu)$ is the spectral response function, and ν_1 and ν_2 are its lower and upper limits. The Planck function $B(\nu, T)$ is given by

$$B(\nu, T) = \frac{C_1 \nu^3}{e^{\frac{C_2 \nu}{T}} - 1} \qquad \text{(A8)}$$

The constants C_1 and C_2 are 1.1910659×10^{-5} mw /(m^2 sr cm^{-4}) and 1.438833 K/cm^{-1}, respectively.

For the AVHRR, Eqn. 11 is evaluated numerically by

$$N(T) = \frac{\sum_{i=1}^{n} B(\nu_i, T)\, \phi(\nu_i)\, \delta\nu}{\sum_{i=1}^{n} \phi(\nu_i)\, \delta\nu} \qquad \text{(A9)}$$

In actual practice at NESDIS, we use Eqn. A9 only to generate look-up tables relating temperature to radiance. There is one table for each channel. Each table specifies the radiance at every tenth of a degree (K) between 180 and 320 K. Thereafter, the tables are used whenever we convert temperature to radiance or vice versa. These tables should be made an integral part of the Pathfinder database.

APPENDIX B: The AVHRR Pathfinder Calibration Working Group

The membership of the AVHRR Pathfinder Calibration Working Group is listed below:

Chair:	C.R.Nagaraja Rao	NOAA/NESDIS
Members:	Peter Abel	NASA/GSFC
	Christopher Brest	Hughes STX
	Robert Cess	SUNY, Stony Brook, NY
	Robert Evans	University of Miami, Miami
	Garik Gutman	NOAA/NESDIS
	Yoram Kaufman	NASA/GSFC
	William Rossow	NASA/GSFC/GISS
	Frank Staylor	NASA/LaRC
	Michael Weinreb	NOAA/NESDIS

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